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Design and Validation of the 2017 University of Idaho Clean Snowmobile: Reduced Speed 800 cc Flex-Fueled Direct-Injection Two-Stroke with Custom Muffler

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Abstract

The University of Idaho's entry into the 2017 Society of Automotive Engineers' (SAE) Clean Snowmobile Challenge (CSC) is a 2013 Ski-Doo MXZ-TNT chassis with a reduced-speed 800 cc direct-injected two-stroke engine, modified for flex-fuel use on blended ethanol fuels. A battery-less direct injection system was used to improve fuel economy and decrease emissions while maintaining a high power-to-weight ratio. A new tuned exhaust was used to accommodate the lowered operating speed of the engine. The engine speed was reduced to increase efficiency and lower noise emissions. Noise was reduced with the addition of strategically placed sound material and the use of a custom muffler. A three-way catalyst was implemented before the muffler to improve conversion efficiency of harmful exhaust emissions. Pre-competition testing had the snowmobile entering the 2017 Clean Snowmobile Challenge weighing 266 kg (587 lb) wet, achieving 13.5 L/100 km (21 mpg), with an E-score of 190 on E0 gasoline, and a J1161 sound magnitude of 67.5 dBA.

Introduction

Snowmobiles present an opportunity for exhilarating winter recreation and enable riders to explore nature in a unique way. However, their use can negatively impact the environment through production of loud noise, high levels of toxic emissions, and poor fuel economy. In the late 1990s, concerns were growing over the impact of snowmobile use in national parks and other public lands. As such, a competition was created through a partnership between the snowmobile industry, conservationists, and the snowmobiling community to challenge college students to develop a cleaner, quieter, and more fuel-efficient snowmobile with the purpose of maintaining land access across the country.

The Clean Snowmobile Challenge (CSC) was first held in 2000 and hosted by the Society of Automotive Engineers (SAE). Manufacturers now produce snowmobiles that meet all National Park Service (NPS) standards in exhaust and noise emissions. The University of Idaho Clean Snowmobile Challenge (UICSC) team has recognized that development is needed in technologies that can be retrofitted on older or higher powered vehicles. This type of technology is important because many rideable areas can only be accessed through private property. Excessively loud and inefficient snowmobiles can cause landowners to restrict access. This means a consumer may add modifications that are more eco-friendly to perpetuate land access. To achieve this goal, the UICSC team focuses on producing auxiliary systems that can be added onto any platform.

The 2017 CSC continues to drive student innovation through rule changes. Most notable this year is the introduction of a vehicle marketability event. This event requires teams to consider modifications from a consumer's standpoint, acting as an additional component to the manufacturer's suggested retail price (MSRP) event [1].

UICSC Snowmobile Design

The 2017 UICSC team continued the use of a direct-injected (DI) 800 cc Rotax two-stroke engine and a 2013 Ski-Doo MXZ-TNT chassis. This selection was based on high power-to-weight ratio, proven rider comfort, low cost, and mechanical simplicity, which weigh heavily into consumer purchasing decisions [2]. These characteristics cause the typical two-stroke to produce more emissions and be louder than a four-stroke of similar power output [3]. In response to these relative deficiencies, the UICSC team has chosen to reduce the maximum operating speed of the engine, which improved overall efficiency and decreased emissions while maintaining performance comparable to that of the Rotax 600 cc DI two-stroke engine. A custom muffler and a close-coupled catalyst were also developed to further improve the powertrain.

Additional components that could not be easily or safely fabricated were selected and tested for improvements over stock hardware. These aftermarket products include a custom track and skis. The chosen track includes studs molded into the track to increase traction on hard packed surfaces. In addition to the handling improvements the track was modified to improve noise and efficiency. The skis are wider and have improved geometry for trail riding.

Calibration Strategy

The addition of components to the power plant requires an engine recalibration. During engine calibration the objective for various loads and speeds varies. At cruising speeds and loads, the engine was calibrated to minimize brake specific fuel consumption (BSFC). However, under high speeds and loads, peak power and engine survivability were the main focus. The UICSC team follows the four step calibration strategy outlined below.

- Step one (injection timing sweep): Change the fuel injection timing while adjusting the injection quantity to replicate the equivalence ratio ϕ from the initial point.
- Step two (injection quantity sweep): Adjust the injection quantity while maintaining the same timing found in step one. This will change the equivalence ratio, allowing the ideal quantity to be found.
- Step three (spark timing): Ignition timing must be adjusted to find an optimal point. This step requires special attention to prevent engine knock.
- Step four (calibration interpolation): After calibrating selected portions of the map the values are then interpolated to populate the remaining test points.

The engine is calibrated with higher resolution near the 5-mode points dictated in the emissions test. The 5-mode test represents loads and speeds that are seen during normal, on-snow usage [1]. So it is more important to refine the calibration near these points rather than far away, meaning an interpolation between these areas provides adequate performance at all operating points. After dynamometer calibration, the entire fuel map was verified on-vehicle and minor adjustments were made for rideability. It is unnecessary to revalidate the points since the exhaust gas composition is matched to the dyno calibration on snow, using the lambda meter. Lambda is a unitless representation of air-to-fuel ratio (AFR), also known as the excess air coefficient. Equation 1 represents the stoichiometric AFR compared to measured AFR. Stoichiometric AFR is achieved when the exact amount of air and fuel is present within the cylinder to completely burn all fuel and oxygen. Stoichiometric combustion leaves no excess air or fuel, only exhaust gases, to be expelled from the exhaust pipe.

$$\phi = \frac{1}{\lambda} = \frac{AFR_{Stoich}}{AFR_{Measured}} \quad (1)$$

To evaluate the effects of each design point on the E-score, the UICSC team created a penalty function, equation 2. The penalty function was developed from the 5-mode emissions score and incorporates power (P), and the weight of the tested mode point (W_m). It shows how many E-score points will be lost at each step of the calibration.

$$F(x) = W_m * \frac{\left(\frac{6*UHC+NO_x}{150}+\frac{CO}{400}\right)}{P} \quad (2)$$

Figure 1 and Figure 2 show steps one and two of the calibration, respectively, where injection quantity is swept while holding “Injection Timing 1” constant. These are referenced to equation 2. These steps are an example of calibrating a single point in the fuel map and must be repeated for every cell in the operational range of the engine. Each data point in the plot takes ~2 minutes to gather and must be repeated until the “j-hook” is completed. This shows that the amount of time needed to properly calibrate is immense, which justifies the interpolation.

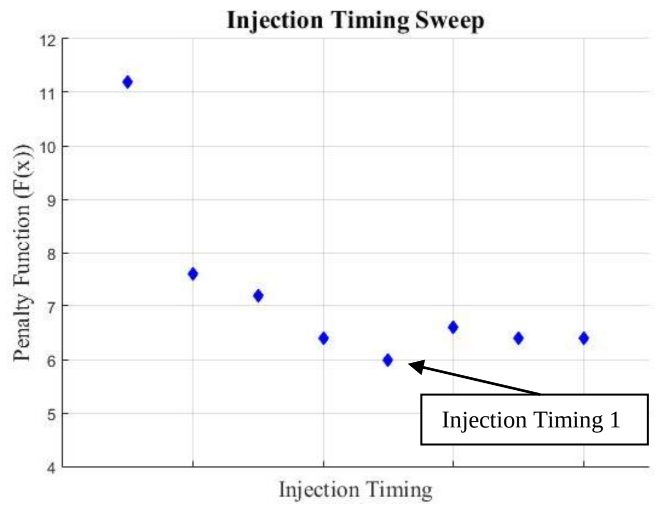

Figure 1. Injection timing sweep.

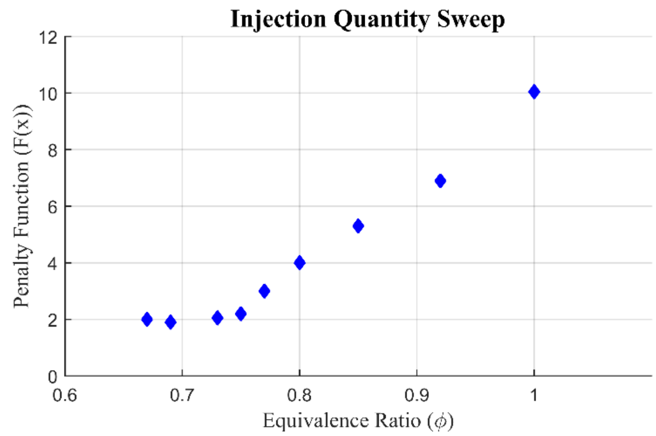

Figure 2. Injection quantity sweep.

All testing was conducted using identical intake and exhaust hardware used on the 2017 platform. Variances in hardware would result in inaccuracies in calibration. The base map was calibrated using 0% ethanol fuel, and after the initial calibration, the ethanol compensation map was developed using the same 4-step procedure described above. A blank catalyst was added to emulate expected back pressure and to avoid damaging the monolith (catalyst substrate) during use of an unrefined fuel map.

Calibration Equipment

A Borghi & Saveri eddy-current dynamometer, model FE-260-S, was used for calibration. Fuel delivery was controlled and measured by a custom fuel cart. Emissions data were collected by a Horiba MEXA-584L 5-gas analyzer. An Innovate LM-2 wideband Oxygen sensor was used to measure AFR. A water brake dynamometer was used to test the calibration in similar conditions to those at the CSC.

Flex-Fuel

The 2017 competition requires the use of ethanol-gasoline mixtures ranging from 0% to 85%. To accommodate this, the UICSC team continued to use the system developed in 2012. This includes a Continental flex-fuel sensor coupled with a custom analog circuit. Due to the reliability of the circuit, no alterations were made [4].

Tuned Pipe

Reducing the speed of the engine from 8000 RPM to 7000 RPM has the adverse effect of moving the engine RPM out of the effective range of the tuned pipe [5]. Operating outside the original design range of the pipe causes mid-range power and efficiency decreases in addition to decreased power at high loads and speeds. In 2016, the UICSC team increased the length of the tuned pipe to mitigate this. The effectiveness of the pipe varies greatly with the temperature of the pipe. The 2016 UICSC calibrated the engine with an un-insulated pipe, but in chassis it was wrapped to reduce the risk of damaging plastics. This led to higher temperatures in the exhaust, causing detonation as a result of the shifted trapping and scavenging pulses. For the 2017 CSC, this problem was resolved through recalibration.

Several sections of a tuned pipe can be modified to alter its performance. Starting from the exhaust port, these include the header, diverging cone, dwell, converging cones, and stinger. The cones affect the intensity of the scavenging and trapping pulses. The overall length affects the timing of these pulses, which determines the engine speed at which the pipe is most effective. In order to accommodate the lower maximum engine speed, the total length of the pipe was extended by 14%. This length was added in the dwell and header [6]. Figure 3 shows where the pipe was extended in-chassis.

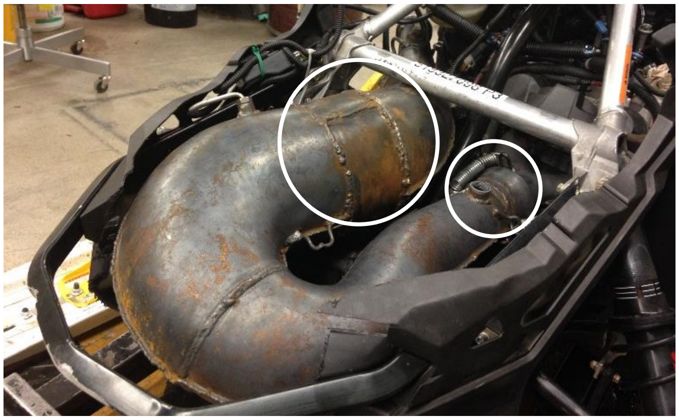

Figure 3. Extended tuned pipe in chassis.

Powertrain Efficiency

Vehicle efficiency is commercially described as fuel economy. Fuel economy is a direct function of powertrain (engine and drivetrain) efficiencies. An efficient powertrain will produce less harmful emissions than a poorly developed one. It is beneficial for design to view the system as a whole rather than develop pieces independently. The UICSC has improved fuel and emissions efficiency in the past primarily by reducing the maximum operating speed of the engine [7].

Drivetrain

Drivetrain refers to every component that achieves propulsion after the engine, specifically the clutches, drivers, bogey idler wheels, and track. The 2017 changes include a ported and studded track, stock drivers, and large rear idlers. Two tests were used to compare the drivetrain efficiencies. A roll-down test was developed to quantify the effects of only the track, drivers, and bogey idler wheels. This test was performed by placing the snowmobile on a platform that was gradually raised from one side. Once the snowmobile rolled fully off the ramp, the angle was recorded. A lower angle equates to a lower rolling resistance. Table 1 shows the comparison between the new track and a fully broken-in track used on the 2017 configuration.

Table 1. The angles at which the snowmobile freely rolls down the platform.

Mileage of track	Angle of Roll	Percent Change
0 km (0 miles)	10.37 °	0%
72.4 km (45 miles)	10.20 °	-1.7%
120.7 km (75 miles)	9.59 °	-7.6%
161+ km (100+ miles)	9.43 °	-9.1%

The test was repeated several times on differing configurations for comparison. The stock snowmobile consists of a 3.1 m (121 in) studded track with 20 cm (8 in) drivers and rear idler bogeys. For the 2016 CSC this was changed to utilize a 3.2 m (128 in) studded track, with 25 cm (10 in) drivers and rear bogeys. The 2017 competition vehicle utilizes a 3.3 m (129 in) studded and ported track with 20 cm (8 in) drivers coupled with 25 cm (10 in) rear idlers. Table 2 compares the 2017, 2016, and stock configurations. All tests incorporated a fully broken-in track.

Table 2. Comparison between the stock, 2016, and 2017 configurations.

Configuration	Angle of Roll	Percent Change From Stock
Stock Configuration	12.60 °	0%
2016 Competition	12.11 °	-3.8%
2017 Competition	9.43 °	-25.2%

A rollout test was used to account for clutching and ski modifications in conjunction with the track and drivers. The above configurations were utilized during this testing. The differences between the two tests were the inclusion of clutching and ski efficiencies. This test was performed by a snowmobile approaching a gate at a constant speed. Once reaching the gate, the rider released the throttle and the snowmobile coasted to a stop. The distance between the rider and the gate was measured. A longer coast down distance correlates to increased drivetrain efficiencies.

Table 3 displays the results of the rollout test with various configurations. The stock and 2016 configuration rollout tests were performed on groomed trails, while the 2017 configuration was tested in loose, slushy snow. The decrease in travel distance at 24 kph (15 mph) with the 2017 configuration is likely due to the conditions and not decreased efficiency.

Table 3. Rollout test results.

Configuration	24 kph (15 mph)	57 kph (35 mph)
Stock	13 m (42 ft)	44m (145 ft)
2016 Configuration	14 m (47 ft)	45.7 m (150 ft)
2017 Configuration	12 m (39.5 ft)	46 m (151 ft)

After completing engine calibration, it was also necessary to recalibrate the clutching. This hardware consists of two pulleys. The first, or primary, affects initial clutch engagement and max engine speed. This was modified to match the peak engine speed from dyno calibration. The other pulley, or driven clutch, primarily affects shift rates and engine braking. These components can be an area of high loss in the drivetrain. Propulsion of the snowmobile is achieved by actively changing the primary clutch diameter in response to the torque from the engine. As this pulley diameter changes, the belt is gripped and rotated, causing the driven clutch to rotate as well. The main losses in this system's efficiency result from belt slip and heat. The secondary clutch contributes most to these losses. Such inefficiencies were mitigated by choosing a spring in the secondary that provides sufficient clamping force to prevent belt slip while keeping friction at a minimum to avoid high heat generation [8].

Fuel Consumption

The measured brake mean effective pressure (BMEP), or engine load, is shown in equation 3. Fuel consumption is measured at various engine speeds and loads to create a BSFC map, as shown in Figure 4. Figure 5 shows the percent difference in BSFC between the 2017 competition snowmobile and stock. Points on the first BSFC map that are lower mean the engine is using the fuel to more efficiently create power. At most speeds and mid-range load, BSFC is held between 250 – 300 g/kW-hr (0.411-0.493 lb/hp-hr). At high speed and loads, the BSFC increased to above 400 g/kW-hr (0.658 lb/hp-hr). This was attributed to the extended tuned pipe not effectively trapping and scavenging under these specific conditions. A positive number in the second plot is interpreted as an increase in engine efficiency.

$$BMEP = \frac{2\pi * T * n_R}{V_d} \quad (3)$$

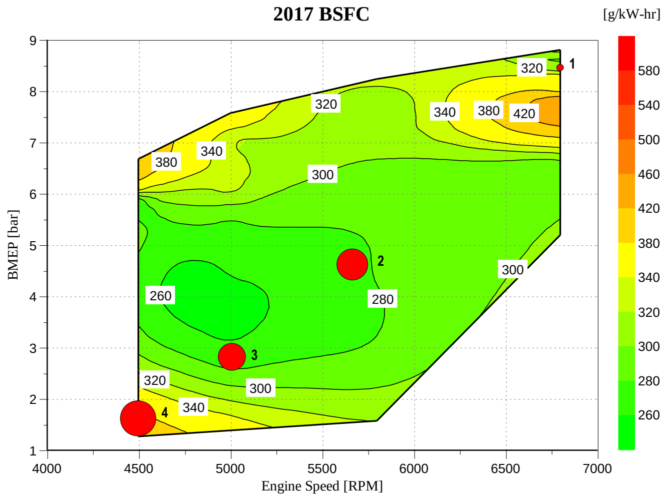

Figure 4. BSFC map post-calibration.

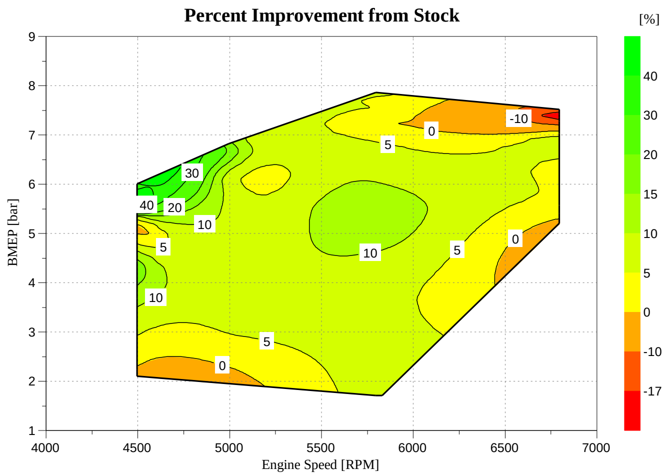

Figure 5. Percent improvement from stock.

Emissions

In previous years the UICSC team has implemented a three-way catalyst at the exit of the muffler to reduce harmful exhaust emissions. A three-way catalyst is both an oxidation and reduction monolith. Reduction refers to the conversion of Oxides of Nitrogen (NO_x) and oxidation converts Carbon Monoxide (CO) and unburned Hydrocarbons (UHC). Even though the UI engine produces a low amount of NO_x, testing has proven that the use of a three-way rather than a two-way catalyst provides better performance with regard to emissions reduction. Figure 6 shows a comparison of various Platinum: Palladium: Rhodium coated catalysts that the UICSC tested. Although the 1:0:1 two-way and 1:20:1 three-way catalyst achieved the same E-score, the three-way catalyst had a quicker light-off time, resulting in better emissions performance during on-snow testing.

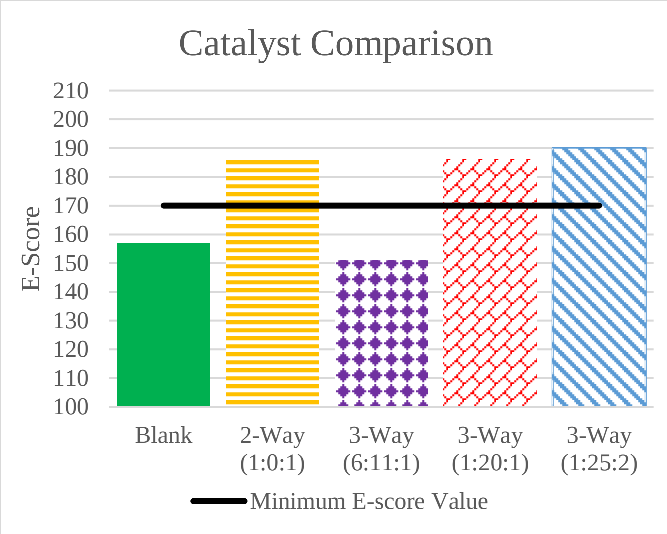

Figure 6. Catalyst comparison.

Previously the catalyst was implemented in the exit of the muffler for ease of packaging. This was achieved by replacing a chamber of the stock muffler with a catalyst, without quantifying changes in acoustic performance, weight, and added backpressure. In this configuration, the catalyst had reduced emission conversion efficiency during prolonged mode 4 testing and stopped converting altogether in mode 5. The redesign of the muffler provided the opportunity to move the catalyst to the entrance of the muffler, as shown in Figure 7, increasing the exhaust gas temperature entering the catalyst. These increased temperatures allow the catalyst to convert emissions in all five modes effectively once the system is heat soaked under normal operation.

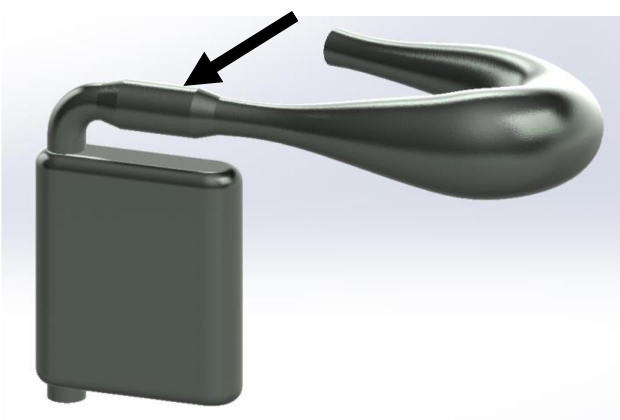

Figure 7. Relocation of catalyst.

Catalyst size and cell density were chosen based on engine flowrates and packaging constraints. Inlet and outlet cones were designed to ensure that flow was laminar across the face of the catalyst, reducing backpressure and improving emissions conversion. The relocated catalyst showed an improvement in emissions performance increasing the E-score from 186 in 2016 to 190. In the previous configuration the catalyst was subject to back-flow of cold ambient air. By relocating the catalyst upstream, the catalyst is able to retain more heat during low-load situations. Metal substrate catalysts are designed to perform in temperatures near 926 C (1700 F). If the temperatures exceed this for a significant amount of time the monolith can be damaged. Considering emissions performance, back pressure, and operational temperature the 1:25:2 three-way catalyst was chosen for the 2017 CSC.

After the addition of the blank catalyst and muffler redesign, emissions were measured throughout the map. Figure 8 shows the brake specific production of UHC (BSHC).

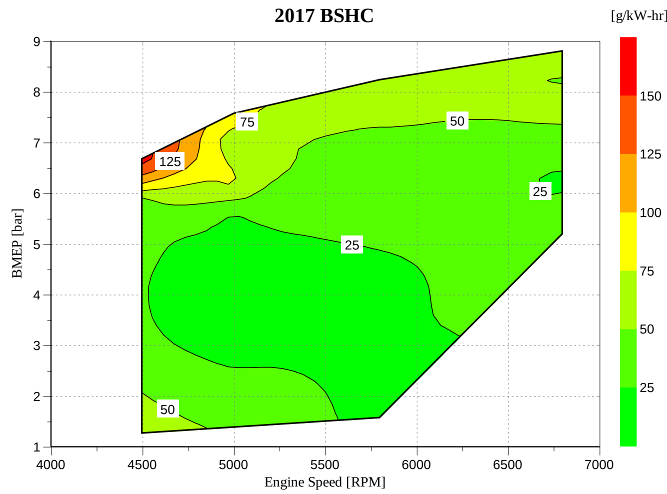

Figure 8. Brake specific UHC production.

Figure 9 and Figure 10 show brake specific CO (BSCO) and Carbon Dioxide (BSCO$_2$) production, respectively. A brake specific NO$_x$ map was not included because very little NO$_x$ is produced by the two-stroke platform [9]. Though Carbon Dioxide (CO$_2$) is not weighed in the E-score, it was included due to the effect of greenhouse gases on the environment.

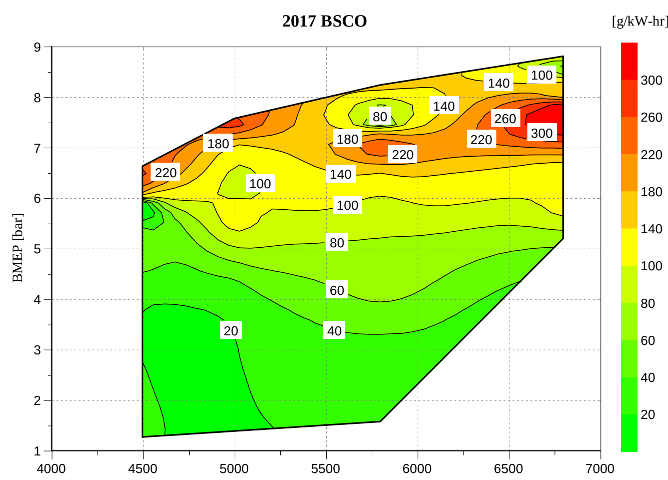

Figure 9. Brake specific CO production.

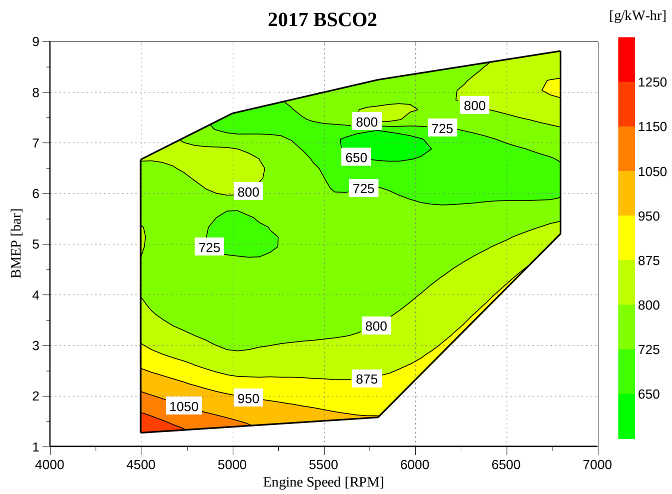

Figure 10. Brake specific CO2 production.

The final E-score for the 2017 configuration was tested to be 190. A comparison of the UI 2017 and 2016 entries and three other team's E-scores are shown in Figure 11. The three schools chosen include a highly advanced four-stroke and a two and four-stroke of similar power to the UI platform. The black line represents the NPS emissions minimum, while 100 is the Environmental Protection Agency (EPA) minimum and 210 is maximum possible E-score.

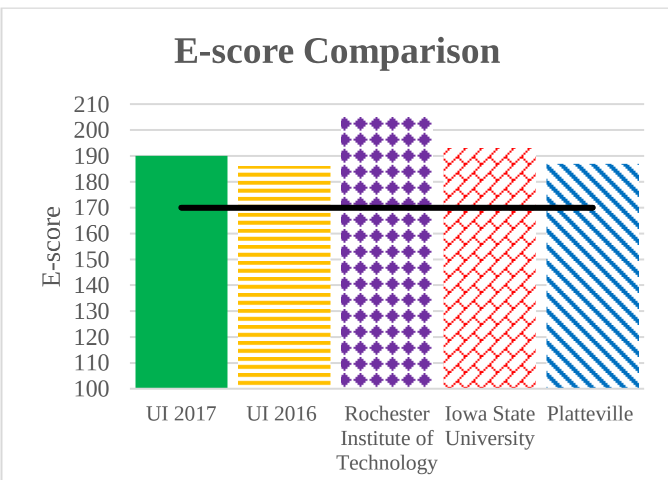

Figure 11. E-score comparison.

Noise

Although the UICSC team has made noise a focus for development in the past, it has remained a problematic area. To further address this issue, the team developed new testing apparatuses and procedures to better understand snowmobile sound production and mitigation. This includes determining sources of noise as well as controlled testing of various noise attenuation devices. All final sound reductions on chassis were found using the J1161 sound test.

Noise Vectoring

The noise vectoring techniques were developed by the UICSC to determine the areas and frequencies on the vehicle that would benefit most from sound reduction. Sound data were collected by microphones placed on a grid on clutch and exhaust sides of the stock snowmobile during stationary operation with the track lifted and operating at an engine speed of ~3800 RPM. The insertion loss at each location was calculated using equation 4 where P_2 is the point of interest relative to the reference point P_1.

$$IL = 20 * log\left(\frac{P_2}{P_1}\right) \qquad (4)$$

During testing, one microphone was kept at a single, central location and used as a control. After testing, the insertion loss at each point was calculated with respect to the control point. Figure 12 and Figure 13 show the differences in sound pressure (dBA) between each tested microphone location on the exhaust and clutch side, respectively. Similar noise output to the control point is represented by yellow, while louder in red and quieter in green. The data points were chosen to analyze as much of the snowmobile as possible, but the intermediate points were interpolated for the figures. The sound pressure values were evaluated at 172 Hz. This frequency was chosen because inspection of the fast Fourier transform (FFT) showed this frequency to be the largest contributor to sound power on both sides of the snowmobile. A silhouette of the competition vehicle is overlaid to better represent the noise vectoring test. Notable areas of noise production on the exhaust side are around the outlet of the muffler and the track. On the clutch side, the loudest areas are at the pulleys and intake.

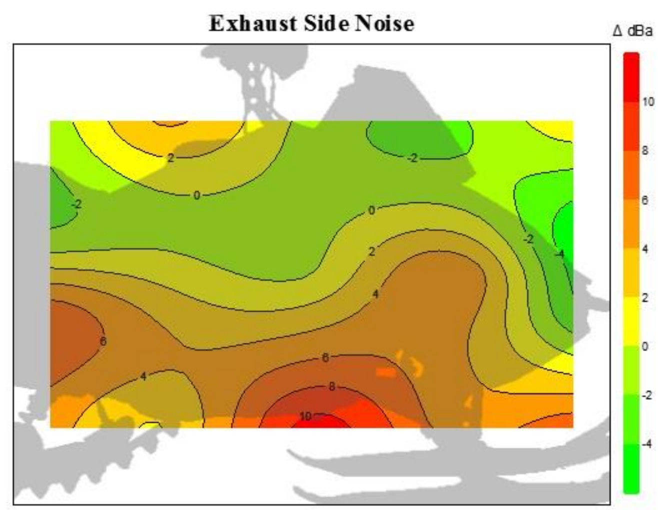

Figure 12. Noise vectoring for exhaust side.

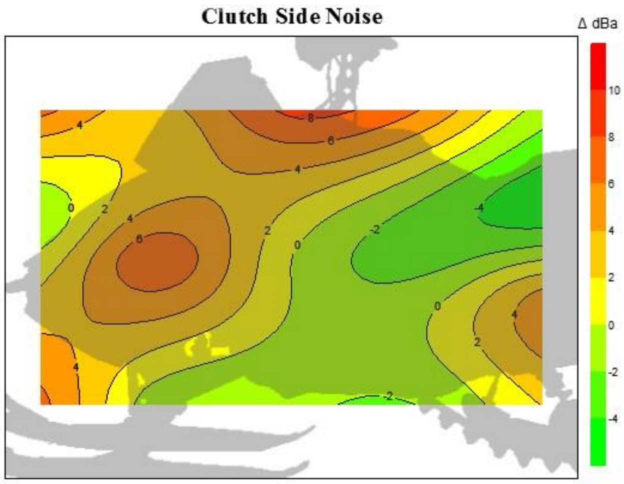

Figure 13. Noise vectoring for clutch side.

Anechoic Sound Box

To improve understanding of sound attenuation, the UICSC team manufactured an anechoic sound box testing apparatus, referred to as the UI sound box (UISB). The initial design of the UISB was based on an existing design, which was used to test the acoustic effectiveness of quarter-wave and Helmholtz resonators [10]. The anechoic sound box was designed to emit pure frequencies through a waveguide (pipe) without interference. The final UISB specifications are given in Table 4.

Table 4. UI Sound Box Specifications.

Speakers [11]	15.88 cm (6.25 in)
Tweeters [11]	4.60 cm (1.81 in)
UI Sound Box	.23 m^3 (8.00 ft^3)
Waveguide Diameter	5.08 cm (2.00 in)
Waveguide Length	4.06 m (13.33 ft)
Studio-foam [12]	10.16 cm (4 .00in)
Audio Amplifier [13]	1100 W
Microphone Locations [14]	45.72 cm (18 .00 in), 137.16 cm (54.00 in), 289.56 cm (114.00 in), 381.00 cm (150.00 in)

The box contains amplified speakers and tweeters acting as a sound source directed into the UISB. The housing was built using 1.91 cm (0.75 in) high density fiber board internally lined with the studio-foam. Attached to the sound box is the waveguide, which extends to the environment with a removable center section. This section in the center of the pipe is removable for the purpose of testing individual acoustic components. The component length was held constant so the waveguide spanned the same distance for each test. Four microphones were placed along the pipe at the specified locations from the outlet of the UISB. The microphone's signals were analyzed using a Digilent electronics explorer board. Figure 14 represents the final configuration of the UISB.

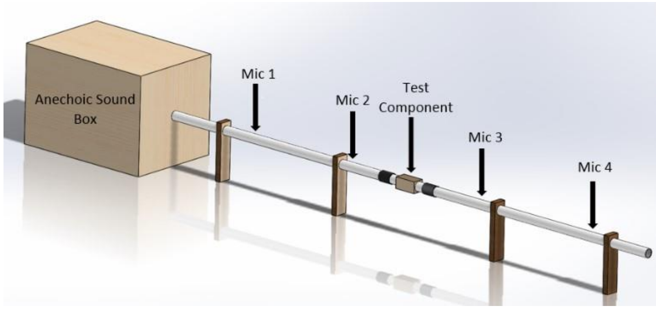

Figure 14. UICSC sound box configuration.

The minimum testable frequency was calculated to be 80 Hz using equation 5 while the maximum, 4000 Hz, was found using equation 6. These equations are the wavelength and narrow pipe assumption, respectively. Wavelength is the distance between two peaks of a sound wave and constrains testing due to waveguide length.

$$\lambda = \frac{c}{f} \qquad (5)$$

$$\lambda > 1.71 * D \qquad (6)$$

When acoustic impedance is added to the travel path of the sound wave, there is a chance for a reflected wave to occur. In this case, acoustic impedance represents barriers, sound absorption materials, or geometric changes. Two microphones were placed before and after the test component to account for the reflected wave [15]. Under ideal testing the distance between each microphone would be equivalent to the wavelength of the tested frequency. Measuring sound phase makes moving the microphones extraneous.

Testing Method

Each test was performed by sweeping frequencies from 80 Hz – 4000 Hz scaled logarithmically. The pressure and phase were recorded allowing the UICSC team to calculate the power transmission coefficient. Due to the complexity of the derivation, this equation is not shown. The power transmission coefficient is interpreted as a percentage of the sound power that is reduced due to a material or geometric change. A positive value represents a reduction in sound and a negative value an increase. These increases may come from a natural resonance of the sound chamber, waveguide, or test component [16]. For example, a transmission power coefficient of .8 indicates that 80% of the sound power is reduced while 20% passes through the component.

Tested Components

Much of the hardware applied to previous UICSC designs was re-evaluated using the improved testing apparatuses and selected based on these results. In addition to this, the capability to test more-complex acoustic devices allowed the team to design more effective solutions.

Sound Material

Using the UISB, the UICSC team retested various sound materials to determine which would mitigate the most abundant frequencies produced by the snowmobile. During the J1161 pass-by test 150, 400, and 1200 Hz and 150, 1200, and 2000 Hz were found to be the primary frequencies for the exhaust and clutch sides, respectively, using FFTs. To compare the various sound materials, power transmission coefficients were used. Table 5 represents these coefficients of the various sound materials at the target frequencies.

Table 5. Power transmission coefficients of various sound materials.

Sound Material	150 Hz	400 Hz	1200 Hz	2000 Hz
Melamine 3-Layer Foam	0.334	0.202	-0.016	0.690
Melamine 3-Layer Foam with Heat Shield	0.259	0.143	0.333	0.133
PAF with Heat Shield	-0.283	0.131	0.166	-0.056
PAF	0.134	0.433	0.331	0.221

Melamine 3-layer foam was the most effective at absorbing the noise at frequencies of 150 and 2000 Hz. While POLYDAMP Acoustical Foam (PAF) absorbed more noise at 400 and 1200 Hz, melamine 3-layer foam was more effective in overall sound absorption. This was determined by inspecting the frequencies near each target point, and determining which material was best across this small range. An example of these data is shown in Appendix A. Using this method, the UICSC team determined the melamine 3-layer foam was best for clutch side and heat-shielded material on the exhaust side. Heat shield was also used in the belly pan due to the high temperatures.

With the appropriate sound material added throughout the engine compartment, there was a 3.0 dBA drop and a 2.0 dBA drop on the clutch and exhaust sides, respectively.

Intake Modifications

To address noise on the intake, two strategies were pursued. A Helmholtz resonator was placed between the primary and secondary air-boxes. The resonator had the added benefit of increasing torque at the design point [6]. A porous foam was added to the intake, yielding a 1 dBA loss on the clutch side.

Muffler Components

Analyzing the results from the 2016 CSC, it was evident that meeting NPS sound needed to be a focus for 2017. To help accomplish this, a custom muffler was designed. To achieve optimal muffler design, the fundamentals of acoustic termination had to be better understood. An optimum design consisted of high noise attenuation with similar back pressure to the stock snowmobile. This was further designed to not greatly add to the weight or complexity of the vehicle. This design was achieved by testing expansion chambers, geometric interference, perforated tubes, and sound material using the UISB. The results of the selected components, which represent a small portion of those tested, are shown in Table 6.The underlined components were used in the final design. The table shows the power transmission coefficients for each of the tested components at frequencies of 150, 500, 1250, and 2000 Hz. These frequencies were chosen by inspecting FFTs of the snowmobile during cruising speeds. 150 Hz is the firing frequency of the engine at 56 kph (35 mph), found using equation 7.

$$f = \frac{n_c * RPM}{n_R * 60} \qquad (7)$$

Table 6. Transmission Coefficients from individual component tests.

		Frequency [Hz]				
Configuration		150	500	1250	2000	Avg.
Expansion Chamber Size [cm x cm x cm (in x in x in)]	**7.6x7.6x20.3 (3x3x8)**	0.008	0.828	0.491	-0.194	0.283
	10.2x10.2x10.2 (4x4x4)	0.296	-0.179	0.518	0.01	0.161
	10.2x10.2x30.5 (4x4x12)	0.287	0.522	-0.037	-0.372	0.100
	15.2x15.2x20.3 (6x6x8)	0.211	-0.31	0.055	0.381	0.084
Sound Material with Weight [g (oz)]	**Fiberglass Blanket 25 (0.89)**	0.062	-0.014	0.135	-0.565	-0.096
	Fiberglass Blanket 50 (1.76)	0.627	0.765	0.073	-0.177	0.322
	Ceramic Blanket 25 (0.89)	0.382	0.234	0.114	-0.343	0.097
	Ceramic Blanket 50 (1.76)	0.367	0.236	0.121	-0.165	0.140
Perforated Hole Density	1/4 in 22%	0.256	0.299	0.227	-0.157	0.156
	1/4 in 40%	0.247	0.119	0.014	-0.13	0.063
	1/4 in 58%	0.2885	0.358	0.682	-0.207	0.280
Deflectors	Round Same Size	0.316	0.238	0.332	0.026	0.228
	V Same Size	0.48	0.113	0.339	-0.000	0.233
	Round Descending Size	0.319	0.161	0.191	-0.081	0.148
Three Expansion Chambers Placed in Series [1=7.6x7.6x20.3 (3x3x8), 2=15.2x15.2x20.3 (6x6x8)]	**1,1,2**	0.265	0.157	0.041	-0.188	0.069
	1,2,1	0.243	-0.087	0.163	-0.469	-0.038
	2,1,1	0.133	0.206	-0.1	0.084	0.081

Muffler Design

The following strategies contributed to the largest reduction in sound: expansion chambers with larger cross-sectional areas, ordering expansion volumes from small to large in series, and “V”-shaped geometric interference plates of the same size. Solidworks was used to simulate fluid flow and back pressure of the muffler components. A flow bench with variable flow rate was used to compare back pressure values to simulations, shown in Table 7. The average difference between the Solidworks simulations and flow bench measurements was 58%. This was due to the simulations being calculated based on steady flow while the flow bench utilizes vacuum motors that create pulses. The UICSC muffler design is called Red Dawn $(AM)^2$.

Table 7. Peak back pressure versus simulation results.

Test Component	Solidworks	Flow Bench
Simple Expansion	.006 bar (.09 psi)	.02 bar (.23 psi)
2013 Stock	.03 bar (.39 psi)	.04 bar (.63 psi)
Red Dawn $(AM)^2$	.04 bar (.51 psi)	.05 bar (.76 psi)

Using this information, the UICSC team designed four mufflers that were simulated through Solidworks for fluid flow and back pressure, while Sidlab was used for transmission loss. Equation 8 represents transmission loss where P(1) and P(r) are the pressure amplitudes measured at distances of 1 m (3 ft) and r [17]. The distance r used in the Sidlab simulation covers the distanced travel through the tuned pipe and muffler equaling 2.4 m (8 ft).

$$TL = 20 * log\frac{P(1)}{P(r)} \tag{8}$$

The Red Dawn $(AM)^2$ muffler performed better than stock at higher frequencies, which are weighted higher in the A-weighted scale [16]. All testing assumed 56.3 kph (35 mph) at 30% throttle. This gives an accurate representation of typical cruising speeds. The results for the Sidlab simulations are shown in Figure 15.

Figure 15. Muffler Sidlab results.

Red Dawn $(AM)^2$ is modeled in Figure 16. The arrows represent the pressure in each chamber of the muffler. Through the design process round edges were placed to ensure the smoothest flow characteristics and reduce the chance of creating high frequency noise [16].

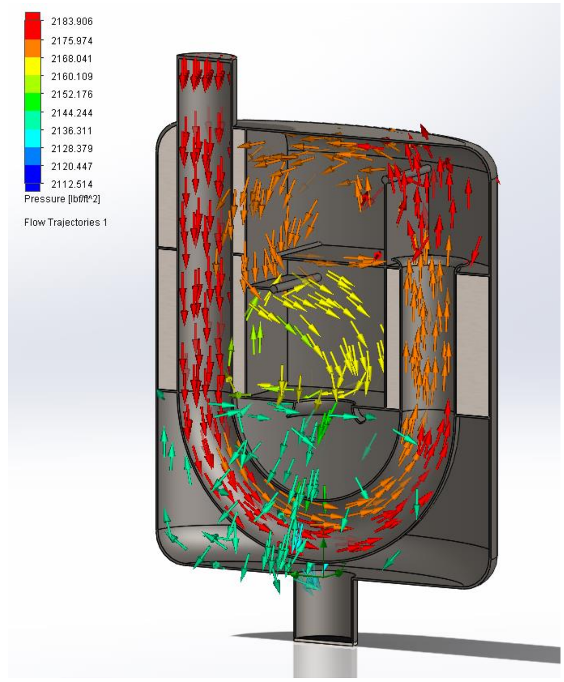

Figure 16. Red Dawn $(AM)^2$ muffler configuration.

The muffler was tested using the J1161 with a result of a 1 dBA loss compared to the 2016 configuration. The UISB also was used to validate the $(AM)^2$ showing that at the lower frequencies there was improved performance over stock, shown in Figure 17.

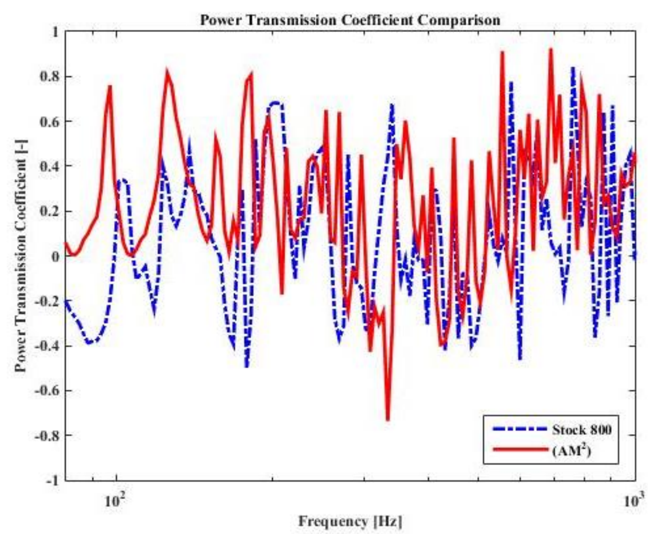

Figure 17. UISB muffler comparison.

Sound Deflection

To reduce noise propagation, deflectors were designed to direct intake noise to the back and front of the snowmobile, keeping noise on the trail. These were tested using the J1161 sound test. An average of a 1 dBA reduction was observed.

Resonance

In previous years the team saw benefits from applying a sound damping material to the tunnel, reducing noise created by tunnel vibration [6]. Four different combinations of damping materials were tested. The test was used to determine which material had the highest damping ratio, as shown in Figure 18. A paint-on damping material was selected for the 2017 CSC, although a final relative sound loss number cannot be measured due to cure time.

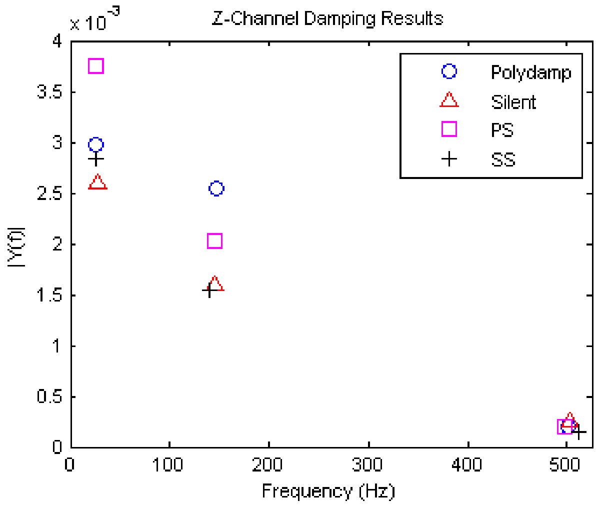

Figure 18. Resonance testing of damping materials.

Dynamic Performance

In general, increased emissions performance, reduced noise, and higher efficiency drivetrain components come at the cost of dynamic performance. More specifically, these components add weight, cost, complexity, and back pressure to the system. These contribute directly to an increase of the risk of failure. Although cost and complexity do not seem to directly correlate to performance, an expensive or difficult-to-repair vehicle will likely not be used to its limits. So, the effects of these components on power need to be considered before making design decisions.

Muffler

A muffler's acoustic performance is typically a function of its increased back pressure. Some back pressure is needed for optimum engine performance, but too much results in power loss. The muffler was designed to be a standalone component and have similar back pressure to the stock component. The measured back pressure of the 2017 muffler with catalyst is 75% higher than stock at the max flowrate of the engine. This resulted in very little power loss from the engine after recalibration. Table 8 represents the various configurations tested.

Table 8. Back pressure comparison to stock.

Configuration	Back Pressure	Change from Stock
Stock	.04 bar (.63 psi)	0%
2016 Configuration	.05 bar (.73 psi)	25%
$(AM)^2$	.05 bar (.76 psi)	25%
$(AM)^2$ With Catalyst	.07 bar (.96 psi)	75%

RAVE Valves

The Rotax adjustable variable exhaust (RAVE) valves change the height of the exhaust port, decreasing exhaust flow at low speeds to improve operation. This change is caused by differing volumetric efficiencies (VE) of the engine. The RAVE valves were calibrated to minimize dips in torque during transition points at higher engine speeds, or in other words, maximize VE. Recalibration became necessary due to the changes in engine performance because of the modified tuned pipe, muffler, and engine speed. The result of these changes is a smooth torque curve allowing for better overall engine performance and ride [6].

Table 9 shows a comparison between the stock and current RAVE calibration maps. Cells that display zero indicate no change in position, while a minus sign indicates a decrease in position and a plus sign indicates an increase in position.

Table 9. RAVE calibration map comparison.

Throttle Percentage (%)	Engine Speed (RPM*1000)							
	4	4.5	5	5.5	6	6.5	6.75	7
0.5	0	0	0	0	-	0	0	0
2	0	0	0	0	-	0	0	0
5	0	0	0	0	-	0	0	0
7	0	0	0	0	-	0	0	0
8	0	0	0	0	-	0	0	0
9	0	0	0	0	-	0	0	0
10	0	0	0	0	-	0	0	0
12.5	0	0	0	0	-	0	0	0
15	0	0	0	-	0	0	0	0
17.5	0	0	0	-	0	0	0	0
20	0	0	0	-	0	0	0	0
25	0	0	0	-	0	0	0	0
30	0	0	0	-	0	0	0	0
35	0	0	0	-	0	0	0	0
40	0	0	-	0	0	0	0	0
50	0	0	-	0	0	0	0	0
60	-	0	0	0	+	+	0	0
90	-	0	0	0	+	+	0	0
100	-	0	0	0	+	+	0	0

Power

With the new muffler design, tuned pipe, and RAVE recalibration, a maximum torque of 117 N-m (86 ft-lb) and a maximum power of 82 kW (110 hp) at 6800 RPM were recorded. The stock 600 cc E-TEC engine is advertised to produce 86 kW (115 hp). The 2017 UICSC configuration fits into the 600 cc engine class.

Weight

A key selling point of the two-stroke platform is its power-to-weight ratio. Reducing weight results in better fuel economy, improved dynamic performance, and decreased rider fatigue. Pre-competition testing had the snowmobile entering the 2017 CSC weighing 266 kg (587 lb) wet, 0.5 kg (1 lb) less than the 2016 configuration. Redesigning the muffler and catalyst allowed the UICSC to reduce the weight of the 2016 muffler from 9.8 kg (21.6 lbs) to 8.7 kg (19.2 lb). The $(AM)^2$ had a 19% reduction in weight compared to stock. Aside from the exhaust components, additional weigh t over stock is due to the sound material.

Table 10 is a comparison of measured snowmobile weights at the 2016 CSC competition [18]. The 2016 and 2017 Idaho configurations are compared to the quietest vehicle at competition and a vehicle making comparable power.

Table 10. Weight comparison to various Universities weights in 2016.

Team	Measured Total Weight
Idaho 2017	266 kg (587 lb)
Idaho 2016	277.1 kg (611 lb)
University of Wisconsin-Madison 2016	258.1 kg (569 lb)
Iowa State 2016	267.2 kg (589 lb)

MSRP

The base price for a 2017 Ski-Doo MXZ-TNT with the 600 cc E-TEC is $11,049. With all modifications included, MSRP of the 2017 UICSC configuration totals $12,699. Components that add to the MSRP were justified by sound reduction, increased performance, reduced exhaust emissions, and increased efficiency. The inclusion of sound material and an intake Helmholtz resonator provided a sound loss of 2.5 dBA at $13.41/dBA. The custom muffler provided an additional 1 dBA drop, along with improved packaging of exhaust treatment components while maintaining cost below the stock muffler. The addition of cost-effective components allows the UICSC snowmobile to achieve a reasonable MSRP compared to stock.

Summary/Conclusions

The University of Idaho has developed a cost-effective flex fuel two-stroke snowmobile capable of running on E0 to E85 blended ethanol gasoline fuel. The DI two-stroke snowmobile maintains the mechanical simplicity and low weight avid riders enjoy, without sacrificing the emissions and noise characteristics necessary to meet NPS standards. The UICSC design produces 82 kW (110 hp), is lightweight at 266 kg (587 lbs) wet, and achieves 13.5 L/100km (21 mpg). Overall sound production, measured using the SAE standard J1161, was recorded at 67.5 dBA. The UICSC design achieves NPS emissions with an E-score of 190. Consumers expect snowmobiles that are clean, quiet, fuel-efficient, and fun to ride. The 2017 UICSC flex-fuel two-stroke reduced-speed snowmobile is an economical response to that demand.

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Definitions/Abbreviations

AFR Air-to-fuel ratio

BMEP Brake mean effective pressure

BSFC Brake specific fuel consumption

CO Carbon monoxide

CO_2 Carbon dioxide

CSC Clean Snowmobile Challenge

DI direct-injected

EPA Environmental Protection Agency

FFT fast Fourier transform

MSRP Manufacturer's Suggested Retail Price

NO_x Nitrous oxides

NPS National Park Service

PAF Polydamp Acoustical Foam

RAVE Rotax adjustable variable exhaust

SAE Society of Automotive Engineers

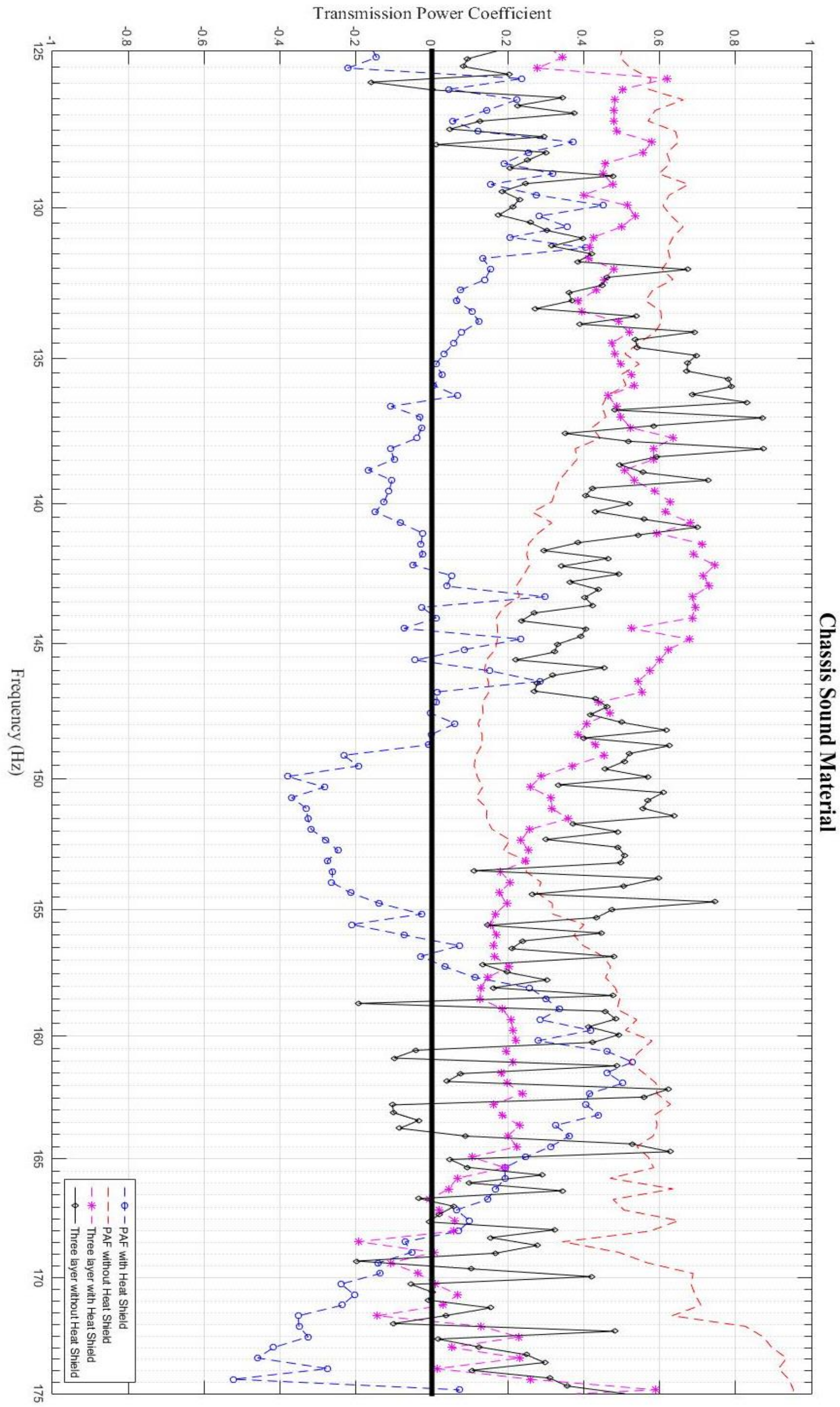
UHC unburned hydrocarbons

UICSC University of Idaho Clean Snowmobile Challenge

UISB University of Idaho sound box

VE Volumetric Efficiency

Appendix A



Chassis Sound Material
Transmission Power Coefficient
Frequency (Hz)
PAF with Heat Shield
PAF without Heat Shield
Three layer with Heat Shield
Three layer without Heat Shield